Investigating the Impact of Tablet Coatings on Gastrointestinal Tract Residence Time and Drug Bioavailability: A Comparative Study of Different Coating Materials

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Abstract

Tablet coatings are crucial for optimizing pharmaceutical formulations by controlling drug release, stability, and bioavailability. The selection of coating material must be tailored to the specific pharmacokinetic properties and therapeutic goals of the drug. This study focuses on three major types of coatings: enteric polymers, lipid-based coatings, and nanoparticle coatings, each offering unique benefits for different drug delivery systems on Gastrointestinal (GSI). Enteric polymers protect drugs from gastric degradation, ensuring targeted release in the intestines, making them ideal for pH-sensitive drugs. Lipid-based coatings are effective for sustained-release formulations, providing controlled drug release over extended periods, which is particularly beneficial for managing chronic conditions. Nanoparticle coatings offer precise drug delivery, allowing for targeted treatment with reduced systemic side effects, and are especially valuable in oncology for delivering chemotherapeutic agents directly to tumor cells. The choice of coating material is guided by preclinical and clinical studies, which evaluate the physicochemical properties, solubility, stability, and permeability of coating materials under simulated gastrointestinal conditions. Advances in nanotechnology and predictive modeling are transforming drug delivery systems, providing opportunities for hybrid coatings that combine the strengths of different materials. These developments promise enhanced precision, scalability, and efficiency in drug formulation. This study highlights the importance of aligning coating properties with therapeutic goals and emphasizes the potential for hybrid systems, 3D printing, and nanotechnology to create more effective, patient-centric drug delivery solutions. Such innovations are expected to improve therapeutic outcomes, reduce dosing frequency, and enhance patient adherence, ultimately advancing the field of drug delivery and improving patient care.

Keywords: Tablet Coatings, Drug Delivery Systems, Enteric Polymers, Lipid-based Coatings, Gastrointestinal (GSI). Nanoparticle Coatings

Significance | This review discusses the importance of tailored tablet coatings to optimize drug release, stability, bioavailability, and therapeutic efficacy.

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Editor Muhammad Asif, Ph.D., And accepted by the Editorial Board December 15, 2024 (received for review October 19, 2024)

Introduction

Tablet coatings are essential components of modern pharmaceutical formulations, playing a pivotal role in improving the efficacy, safety, and patient compliance of oral medications. The primary functions of tablet coatings include protecting the active pharmaceutical ingredient (API) from environmental factors, controlling the release profile of the drug, and masking unpleasant tastes, which significantly enhances patient adherence to treatment

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Please Cite This:
Kabir, M. et al. (2024). "Investigating the Impact of Tablet Coatings on Gastrointestinal Tract Residence Time and Drug Bioavailability: A Comparative Study of Different Coating Materials", Journal of Angiotherapy, 8(12),1-10,10103

regimens (Arora et al., 2019; Ahmed et al., 2021). However, tablet coatings serve a broader purpose than these conventional roles, as they also influence the drug's interaction within the gastrointestinal tract (GIT), potentially altering its absorption and systemic bioavailability (Seo et al., 2020). This relationship between tablet coatings and drug delivery is crucial for the development of advanced drug delivery systems that optimize therapeutic outcomes (Arafat et al., 2023).

The gastrointestinal tract poses several challenges to oral drug delivery due to its dynamic environment, which includes variations in pH, enzymatic activity, and transit time. These factors can impact how a drug is dissolved, absorbed, and distributed in the body. For example, immediate-release formulations often dissolve too quickly, resulting in rapid absorption that may not provide sustained therapeutic effects. In contrast, delayed-release formulations, facilitated by specialized coatings, allow for the controlled release of the API at specific sites within the GIT, thereby optimizing the therapeutic impact (Reddy et al., 2013; Dasalkar et al., 2023). This highlights the need for coatings that can be tailored to the unique characteristics of the GIT, ensuring that drugs are released at the appropriate location and at the correct rate to maximize efficacy.

This study focuses on three distinct types of tablet coatings: enteric polymers, lipid-based coatings, and nanoparticle-based coatings. Enteric coatings are designed to protect the API from the acidic environment of the stomach, allowing for drug release in the more alkaline conditions of the intestines. These coatings are particularly beneficial for drugs that may be degraded by stomach acid or are intended for absorption in the intestines (Basu et al., 2013). Lipid-based coatings, which are hydrophobic in nature, slow down the release of the API, extending the residence time of the drug in the GIT (Fernandes et al., 2019). This extended release can help achieve more controlled absorption, preventing peaks and troughs in drug concentration that can lead to suboptimal therapeutic outcomes.

Among the most advanced coating technologies are nanoparticle-based coatings, which offer significant advantages in terms of site-specific drug delivery and improved bioavailability, particularly for poorly soluble drugs. Nanoparticles can be engineered to release their payload at precise locations within the GIT, enhancing the absorption of drugs that otherwise may have limited solubility or bioavailability (Tran et al., 2023). Despite the growing interest in these advanced coating techniques, there is a lack of comprehensive research directly comparing the performance of enteric, lipid-based, and nanoparticle coatings in a systematic manner (Mute & Shelar, 2024).

The present study aimed to provide a thorough comparison of these coating types, investigating their effects on drug absorption, residence time, and overall therapeutic efficacy. The results of this study will have significant implications for the design of future drug delivery systems, especially for medications with narrow therapeutic indices or challenging pharmacokinetic profiles. Understanding how these coatings impact drug performance is crucial for advancing pharmaceutical formulations and improving patient outcomes in clinical practice (Zaid, 2020; Kapoor et al., 2020).

2. The Role of Enteric Polymers in Drug Delivery Systems

Enteric polymers play a crucial role in modern pharmaceutical formulations due to their ability to withstand the acidic pH of the stomach and dissolve at higher pH levels in the intestines. These coatings are specifically designed to protect the active pharmaceutical ingredient (API) from degradation by gastric acids, enabling site-specific drug release and improving the bioavailability of drugs that would otherwise be compromised by stomach acidity. Enteric polymers have become a cornerstone in the development of oral drug delivery systems, especially for medications that require protection from gastric degradation or need targeted release in specific regions of the gastrointestinal tract (GIT). This section explores the characteristics, mechanisms, applications, and challenges associated with enteric polymers, offering a comprehensive understanding of their pivotal role in drug delivery.

2.1 Characteristics and Types of Enteric Polymers

Enteric polymers are designed to exhibit pH-dependent solubility, a feature that is central to their functionality. These polymers are insoluble in the acidic pH of the stomach but dissolve when exposed to the higher pH conditions typically found in the small intestine. Some of the most commonly used enteric polymers include cellulose acetate phthalate (CAP), hydroxypropyl methylcellulose phthalate (HPMCP), methacrylic acid copolymers, and polyvinyl acetate phthalate (PVAP) (Table 1).

Cellulose acetate phthalate (CAP) and hydroxypropyl methylcellulose phthalate (HPMCP) were among the first enteric polymers developed and are widely used due to their robust resistance to acidic environments (El-Malah & Nazzal, 2010). These polymers are stable in the stomach's acidic conditions and dissolve effectively in the mildly alkaline pH of the small intestine, making them ideal for the delivery of drugs that need to bypass the stomach. Methacrylic acid copolymers, often marketed under trade names like Eudragit, offer greater flexibility. These copolymers allow for the customization of dissolution pH thresholds, making them suitable for targeted drug release within different regions of the GIT. This versatility is particularly advantageous when formulating drugs that require specific pH conditions for optimal release.

The primary mechanism by which enteric polymers function is their pH-dependent solubility. At the low pH levels (1.5–3.5) found in the stomach, these polymers remain intact, forming a protective layer around the API (Prajapati et al., 2016). This prevents the premature release and degradation of the drug by the acidic

environment. As the formulation transitions from the stomach into the small intestine, where the pH is typically above 5.5, the enteric polymer begins to dissolve, triggering the release of the drug at the intended site of absorption. This mechanism ensures that the drug is protected from gastric degradation and released at the appropriate site in the GIT, thereby enhancing the therapeutic efficacy of the drug (Pandey et al., 2023).

2.2 Applications of Enteric Polymers

The use of enteric coatings is widespread, particularly for delayed-release formulations. One of the most common applications is the delivery of proton pump inhibitors (PPIs) such as omeprazole. PPIs are highly susceptible to degradation in the stomach due to their instability in acidic environments. By applying an enteric coating, these drugs can bypass the stomach and be released in the small intestine, where they can exert their therapeutic effect without being destroyed by gastric acid (Barimani & Kleinebudde, 2018).

Another significant application of enteric polymers is in the oral delivery of peptides and proteins, such as insulin, which are prone to enzymatic degradation in the stomach. Enteric polymers shield these delicate molecules during their passage through the stomach, allowing for their controlled release in the intestine, where enzymatic activity is lower and absorption conditions are more favorable. This is particularly important for biologic drugs that cannot be administered by injection and for which oral delivery could improve patient compliance.

Furthermore, enteric polymers have found utility in colon-targeted drug delivery systems. These systems are primarily used for the treatment of inflammatory bowel diseases (IBD), such as ulcerative colitis and Crohn's disease. In this application, methacrylic acid copolymers are particularly valuable because they can facilitate drug release specifically in the colon, where the pH is higher, and where microbiota-mediated metabolism can aid in the controlled release of the drug (Chambliss, 2022). This targeted delivery can help reduce systemic side effects and ensure that the medication is delivered precisely where it is needed.

3. **Lipid-Based Coatings and Sustained Release**

Lipid-based coatings have gained considerable attention in pharmaceutical sciences due to their ability to extend drug release and enhance therapeutic efficacy (Hafeezuallah et al., 2015). Composed of hydrophobic substances like glyceryl behenate, carnauba wax, and hydrogenated castor oil, these coatings act as a protective barrier around tablets, regulating water penetration and modulating drug dissolution rates (Martins et al., 2013). By slowing down the drug release process, lipid coatings ensure prolonged therapeutic effects, reducing the frequency of drug administration and improving patient adherence to treatment regimens (Dineshmohan et al., 2015). This section delves into the characteristics, mechanisms, applications, and challenges associated with lipid-based coatings in drug delivery systems (Figure 1).

3.1 Characteristics and Mechanisms of Lipid-Based Coatings

The key feature of lipid-based coatings is their hydrophobic nature, which directly impacts the kinetics of drug release. Unlike enteric coatings that rely on pH-dependent solubility, (Figure 2) lipid coatings are generally insoluble in gastrointestinal fluids (Albertini et al., 2015). These coatings work by creating a physical barrier that controls the diffusion of water and drug molecules. Upon entering the gastrointestinal tract, the hydrophobic coating limits the rate at which water permeates, delaying the dissolution of the active pharmaceutical ingredient (API). This results in a controlled and gradual release of the drug over an extended period, ensuring sustained therapeutic effects.

The rate of drug release from lipid-coated formulations depends significantly on the thickness and composition of the lipid layer. A thicker lipid layer or higher lipid content in the coating typically leads to a slower release profile, making lipid coatings an ideal choice for sustained-release formulations (Passerini et al., 2010). Additionally, lipid coatings can be tailored for site-specific drug release by incorporating other excipients or modifying the coating structure. This versatility allows lipid coatings to be used in various therapeutic applications, ranging from systemic drug delivery to localized treatment of gastrointestinal disorders.

3.2 Applications of Lipid-Based Coatings

Lipid-based coatings are particularly beneficial for drugs that require prolonged therapeutic effects. Chronic conditions such as hypertension, diabetes, and arthritis often require consistent drug levels to maintain efficacy and minimize fluctuations (Balducci et al., 2011). Lipid-based sustained-release formulations can help achieve this by maintaining steady plasma drug concentrations, reducing side effects, and improving therapeutic outcomes. By extending the gastrointestinal residence time of the tablet, lipid coatings ensure that the drug is available for absorption over a longer period, increasing bioavailability and overall therapeutic efficacy (Albertini et al., 2015).

A key application of lipid-based coatings is in the development of once-daily formulations. Drugs like metformin and propranolol, which usually require multiple daily doses, can be reformulated into sustained-release tablets using lipid coatings. This not only enhances patient adherence but also reduces the burden on healthcare systems by simplifying the dosing schedule (Dineshmohan et al., 2015). Lipid coatings are also particularly useful in delivering poorly soluble drugs, which often pose challenges in achieving therapeutic plasma concentrations. By controlling the rate of release and absorption, lipid-coated formulations improve the bioavailability of these drugs, enabling more effective treatment at lower doses (Martins et al., 2013). Lipid-based systems have been applied in the delivery of anticancer agents

and immunosuppressants, where precision and consistent release are critical for therapeutic success.

The primary advantage of lipid-based coatings lies in their ability to create sustained-release profiles without necessitating complex chemical modifications of the drug molecule. This makes lipid coatings a cost-effective and versatile option for pharmaceutical manufacturers (Hafeezuallah et al., 2015). Additionally, these coatings protect the API from environmental degradation, such as oxidation and moisture exposure, which enhances the stability and shelf life of the formulation.

3.3 Challenges and Limitations

Despite their advantages, lipid-based coatings present some challenges. One significant concern is the potential for variability in drug release profiles due to differences in gastrointestinal conditions, such as pH and motility. Variations in these factors may affect the performance of lipid-coated formulations, making it essential to conduct extensive in vivo testing to ensure consistent drug release (Passerini et al., 2010). Furthermore, the development of lipid-based coatings requires careful formulation and manufacturing processes, as the consistency of the lipid layer's thickness and uniformity is crucial to achieving the desired release rate. Any inconsistencies can lead to problems such as dose dumping, where a large amount of the drug is released too quickly, potentially causing toxicity or adverse effects (Table 2, Table 3).

Lipid-based coatings represent a promising and versatile technology for sustained-release drug delivery. By extending the release of active ingredients and protecting them from environmental degradation, these coatings enhance drug stability, bioavailability, and therapeutic outcomes. Although challenges remain, particularly regarding variability in drug release and manufacturing complexities, ongoing research and advancements in formulation technologies will continue to improve the efficacy and reliability of lipid-coated drug delivery systems.

4. **Nanoparticle-Based Coatings for Targeted Drug Delivery**

Nanoparticle-based coatings represent a revolutionary advancement in drug delivery systems, enabling precise and controlled drug release with unparalleled accuracy (Chen et al., 2019) (Table 2). Composed of materials such as silica, chitosan, and various polymers, these coatings enhance the bioavailability and therapeutic efficacy of drugs (Khodaverdi et al., 2022). Their nanoscale size and customizable surface properties allow nanoparticles to cross biological barriers, facilitate site-specific drug delivery, and improve permeability, addressing challenges that traditional drug formulations often face (Bhardwaj, 2022). This section explores the mechanisms, applications, advantages, and challenges associated with nanoparticle-based coatings in drug delivery (Figure 3).

4.1 Mechanisms of Action in Targeted Delivery

The effectiveness of nanoparticle-based coatings lies in their ability to traverse biological barriers and deliver drugs directly to targeted sites. With sizes ranging from 1 to 100 nanometers, nanoparticles are small enough to penetrate tissues and access cellular compartments that are typically difficult for larger particles or uncoated drugs to reach (Fortuni et al., 2019).

Additionally, their surface properties can be modified through chemical adjustments or the addition of ligands, enabling receptor-mediated targeting of specific tissues or cells (Khodaverdi et al., 2022).

Nanoparticle-based coatings can also enhance the solubility and stability of poorly water-soluble drugs by encapsulating the active pharmaceutical ingredient (API) within a protective matrix. For instance, silica nanoparticles improve the dissolution rates of hydrophobic drugs, facilitating better absorption in the gastrointestinal tract (Chen et al., 2019). Chitosan nanoparticles, known for their mucoadhesive properties, help prolong the residence time of the drug at the site of absorption, further enhancing bioavailability (Fortuni et al., 2019). Another crucial mechanism is the controlled release of drugs from the nanoparticle matrix. By manipulating the coating's composition and structure, drug release can be precisely regulated to achieve sustained or pulsatile release, catering to specific therapeutic needs (Bhardwaj, 2022). This level of control is especially beneficial for drugs with narrow therapeutic windows or those requiring localized action, such as in cancer or inflammation therapies (Khodaverdi et al., 2022).

4.2 Applications and Advantages of Nanoparticle-Based Coatings

Nanoparticle-based coatings have proven to be highly versatile in overcoming various therapeutic challenges. One prominent application is in the delivery of chemotherapeutic agents. Cancer treatments often face off-target effects and systemic toxicity due to drugs being distributed nonspecifically (Khodaverdi et al., 2022). Nanoparticle coatings, designed to target tumor cells specifically, reduce these adverse effects while improving the treatment's efficacy (Chen et al., 2019). For example, nanoparticles functionalized with ligands can selectively bind to receptors overexpressed on cancer cells, delivering the drug payload directly to the tumor site (Bhardwaj, 2022).

Nanoparticle coatings are also instrumental in treating infectious diseases. Antibiotics encapsulated in nanoparticles show enhanced stability and targeted delivery, addressing challenges such as drug resistance and poor tissue penetration (Fortuni et al., 2019). Chitosan-coated nanoparticles, for instance, have been used to deliver antibacterial agents to biofilms, enhancing the efficacy of treatments by disrupting resistant structures (Khodaverdi et al., 2022).

4.3 Challenges and Future Perspectives

Despite the numerous advantages, nanoparticle-based coatings face certain challenges. One of the main concerns is the potential toxicity and long-term effects of nanoparticles within the body. Although materials like silica and chitosan are generally regarded as safe, their biocompatibility must be thoroughly evaluated to minimize adverse reactions (Khodaverdi et al., 2022). Additionally, the production of nanoparticles is often complex and costly, which can limit their widespread adoption, particularly in resource-constrained environments (Chen et al., 2019). Regulatory hurdles and the need for rigorous quality control also complicate the commercialization process (Ahmar et al., 2021).

5. Physicochemical Properties and Their Role in Coating Effectiveness

The effectiveness of tablet coatings is significantly influenced by the physicochemical properties of the materials used, including solubility, pH sensitivity, and hydrophobicity (Arora, Rathore, & Bharakatiya, 2019; Ahmed, Patil, Khan, & Khan, 2021). These characteristics dictate how the coating interacts with the gastrointestinal environment, controls drug release, and ultimately enhances therapeutic efficacy (Seo, Bajracharya, Lee, & Han, 2020). Through careful selection and customization of these properties, pharmaceutical scientists can optimize the bioavailability and targeted delivery of active pharmaceutical ingredients (APIs) (Basu, De, & Dey, 2013; Ganguly et al., 2022).

5.1 Solubility and pH Sensitivity

Solubility is crucial in determining how a coating behaves in different regions of the gastrointestinal tract. For instance, enteric polymers such as cellulose acetate phthalate and methacrylic acid copolymers are designed to remain insoluble in the stomach's acidic environment but dissolve in the more neutral pH conditions of the intestines (Reddy, Navaneetha, & Reddy, 2013). This pH-sensitive behavior is particularly useful for protecting drugs that are unstable or irritating in acidic conditions, ensuring their release in the desired intestinal site (Basu et al., 2013; Ahmed et al., 2021).

In contrast, lipid coatings, which are less reliant on solubility, depend on their hydrophobic properties to regulate drug release (Ganguly et al., 2022). Materials like glyceryl behenate and hydrogenated castor oil form barriers that control water penetration and drug diffusion. These coatings are particularly effective for drugs requiring sustained release, such as those used in Prolonged disease management (Sah, Jangdey, & Daharwal, 2014).

The combination of solubility and pH sensitivity has also led to the development of hybrid coatings. These dual-functional systems combine enteric polymers with lipid-based materials to achieve both pH-sensitive and sustained-release properties, making them ideal for complex therapeutic regimens, such as multi-drug combinations or drugs with challenging pharmacokinetics (Toschkoff et al., 2015).

5.2 Hydrophobicity and Nanoparticles

Hydrophobicity significantly affects drug release rates and stability (Pandey et al., 2023). Hydrophilic coatings dissolve rapidly in gastrointestinal fluids, while hydrophobic materials like lipids form slow-release systems that sustain drug levels over extended periods (Arora et al., 2019). This property is crucial for drugs with narrow therapeutic windows, as it ensures steady plasma concentrations and minimizes the risk of dose dumping (Pal et al., 2023). Nanoparticles enhance this process by offering unmatched versatility. These materials can be engineered to exhibit hydrophobic, hydrophilic, or amphiphilic properties, depending on therapeutic needs (Khan et al., 2015).

Moreover, nanoparticles' small size and large surface area allow them to efficiently interact with biological barriers and provide precise control over drug release (Dineshmohan, 2015). They can encapsulate APIs within a protective matrix, improving stability and enabling targeted delivery to specific tissues or cells, such as cancer cells, reducing systemic toxicity (Martins, Siqueira, Machado, & Freitas, 2013).

5.3 Comparative Effectiveness of Coating Materials

The choice of coating material largely depends on the drug's needs and therapeutic goals (Muliadi & Sojka, 2010). Enteric polymers excel at pH-sensitive release, protecting drugs from gastric degradation and enabling site-specific delivery in the intestines (Toschkoff et al., 2015). Lipid coatings are ideal for sustained-release formulations, which are effective for Continual disease management (Pal et al., 2023). Nanoparticle coatings offer the most comprehensive solution, integrating multiple functionalities for targeted and controlled release, making them suitable for conditions like cancer where precision is crucial (Khan et al., 2015).

6. Tailored Approaches to Tablet Coating Formulation

The choice of tablet coating material is pivotal in determining the success of pharmaceutical formulations, impacting drug stability, release kinetics, and bioavailability. The selection process must align with the drug's pharmacokinetic profile, therapeutic goals, and intended site of action. Coating materials like enteric polymers, lipid-based coatings, and nanoparticle coatings are designed to address specific drug delivery needs, optimizing therapeutic outcomes

6.1 Aligning Coating Properties with Therapeutic Goals

Each drug presents unique challenges, requiring tailored coating solutions. For example, drugs requiring immediate therapeutic action, such as analgesics or antipyretics, benefit more from rapid-dissolving coatings that disintegrate quickly in the gastrointestinal tract. On the other hand, drugs for enduring conditions like hypertension or diabetes are better suited to sustained-release

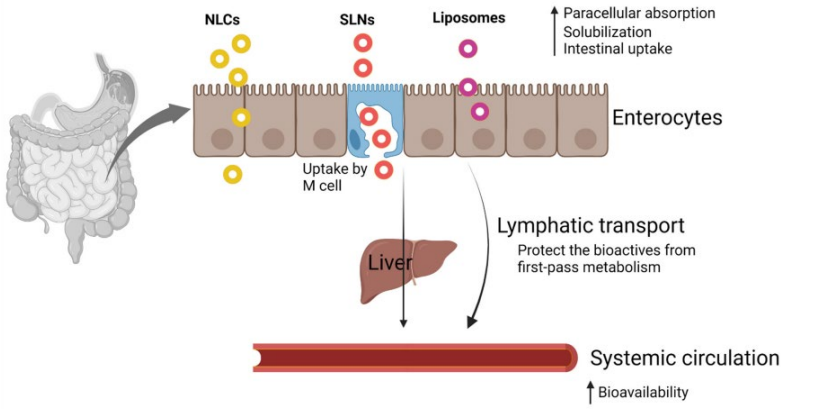

Figure 1. Lipid-based in formulations-controlled drug (Subramanian et al. 2021)

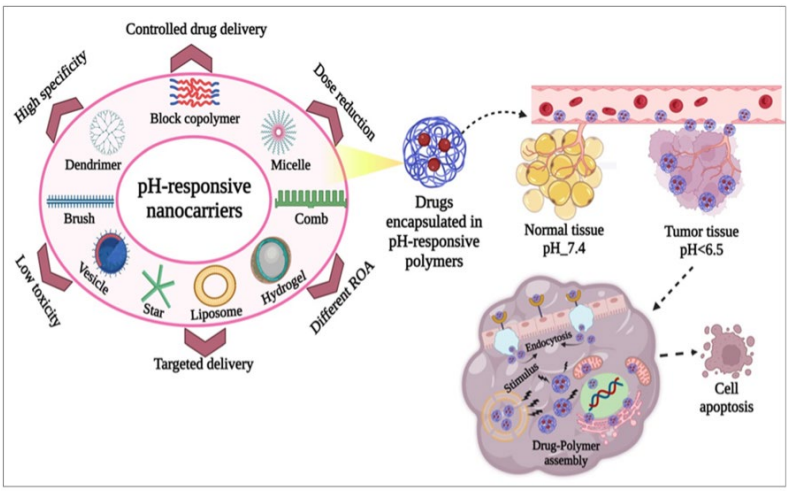

Figure 2. pH-responsive ploymers for drug delivery (J. Singh et al., 2023)

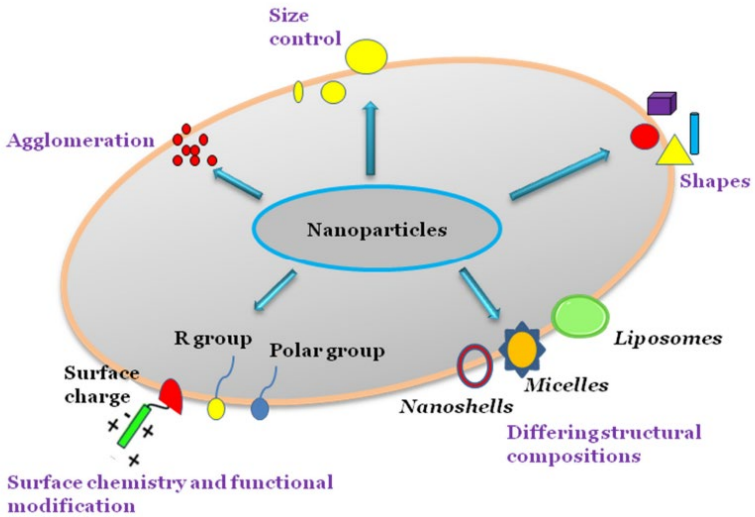

Figure 3. Nanoparticles as Drug Delivery Systems (Yusuf et al. 2023)

Table 1. Characteristics and Mechanisms of Enteric Polymers

Property/Mechanism	Description	Examples	References
pH-Dependent Solubility	Insoluble in stomach acid (pH 1.5–3.5), dissolves at intestinal pH (>5.5)	CAP, HPMCP, Methacrylic acid copolymers	Garg & Gupta (2019); Wang et al. (2020)
Protective Coating	Prevents drug degradation in acidic environments	Applied to PPIs, peptides, proteins	Bhardwaj et al. (2019)
Customizable Release	Adjusts dissolution threshold for site-specific drug delivery	Eudragit polymers	Patra et al. (2022)
Mechanism of Action	Forms a protective barrier in acidic conditions; dissolves and releases drugs in the intestine	APIs for IBD, Crohn's disease, IBS	Langer & Peppas (2020)

Table 2. Applications and Benefits of Lipid-Based Coatings

Application	Mechanism	Advantages	References
Sustained Release	Creates a hydrophobic barrier to regulate water penetration and drug release	Reduces dosing frequency; improves adherence	Narisawa et al. (2020)
Once-Daily Formulations	Gradual dissolution for prolonged therapeutic effect	Simplifies dosing schedules	Chourasia & Jain (2018)
Poorly Soluble Drugs	Enhances solubility and bioavailability	Improves therapeutic efficacy at lower doses	Bhardwaj et al. (2019)
Protective Coating	Shields drugs from oxidation and moisture	Extends shelf life and stability	Wang et al. (2020)
Chronic Disease Management	Maintains steady plasma drug levels	Reduces side effects, minimizes plasma fluctuations	Langer & Peppas (2020)

Table 3. Applications and Challenges of Nanoparticle-Based Coatings

Feature/Challenge	Description	Examples/Impacts	References
Enhanced Bioavailability	Improves solubility, stability, and absorption of poorly soluble drugs	Insulin, hydrophobic APIs	Bhardwaj et al. (2019)
Targeted Drug Delivery	Site-specific delivery using receptor-mediated mechanisms	Chemotherapy, antibiotic resistance	Narisawa et al. (2020)
Crossing Biological Barriers	Nanoparticles penetrate tissues and barriers like the BBB	Neurological disease treatments	Wang et al. (2020)
Controlled Release	Stimuli-responsive nanoparticles for precision in drug delivery	pH-sensitive delivery in tumor environments	Patra et al. (2022)
Challenges	Potential toxicity, high production costs, and regulatory barriers	Complex manufacturing processes	Langer & Peppas (2020)
Future Innovations	AI-driven design, smart nanoparticles responsive to pH and temperature	Improved precision and cost-efficiency	Wang et al. (2020)

coatings, such as those made from lipid materials like glyceryl behenate and hydrogenated castor oil. These hydrophobic barriers regulate water penetration, ensuring prolonged drug release and improving patient compliance by reducing dosing frequency

6.2 Nanoparticle-Based Coatings

Nanoparticle coatings provide precision and versatility, making them ideal for drugs with narrow therapeutic windows or complex delivery requirements. These coatings facilitate targeted delivery to specific tissues, minimizing systemic side effects and enhancing therapeutic efficacy. Nanoparticles are particularly useful in oncology, where they enable chemotherapeutic agents to directly target tumor cells, sparing healthy tissues and reducing toxicity

6.3 Guiding Development with Preclinical and Clinical Studies

The development of tablet coatings is guided by extensive preclinical and clinical studies. Preclinical studies assess the physicochemical properties of the coating material, simulating gastrointestinal conditions to predict its in vivo performance. Clinical trials further evaluate the safety, efficacy, and pharmacokinetics in human subjects. For instance, nanoparticle-coated drugs have shown superior bioavailability compared to conventional formulations, particularly for poorly soluble APIs Additionally, advances in nanotechnology and predictive modeling are making nanoparticle coatings more feasible for large-scale production.

7. Discussion

The role of tablet coatings in pharmaceutical formulations is fundamental to the optimization of drug delivery systems, influencing factors such as drug stability, release kinetics, and bioavailability. Coating materials, including enteric polymers, lipid-based coatings, and nanoparticles, are selected based on the specific properties of the drug, the therapeutic goals, and the pharmacokinetic requirements of the formulation. Each type of coating has its unique advantages and applications, and understanding these materials' physicochemical properties allows pharmaceutical scientists to design effective, patient-centric drug delivery systems.

7.1 Enteric Polymers and pH-Sensitive Coatings

Enteric coatings are designed to protect the drug from the acidic environment of the stomach and ensure its release in the more neutral pH of the intestines. These coatings are particularly valuable for drugs that are unstable in gastric acid or for those that could cause irritation in the stomach lining. By utilizing pH-sensitive materials such as cellulose acetate phthalate or methacrylic acid copolymers, researchers can create coatings that remain insoluble in the stomach and dissolve only in the more alkaline conditions of the intestines. This pH-sensitive release ensures that drugs are delivered at the desired site of action, thereby preventing degradation and ensuring effective absorption (Baus et al, 2013).

The use of enteric coatings has been demonstrated in the successful formulation of proton pump inhibitors like omeprazole. These drugs require protection from gastric acid, and enteric coatings allow the drug to remain intact until it reaches the intestines, where it can be absorbed effectively. Furthermore, advances in coating technology have allowed for the fine-tuning of solubility and release profiles, which is particularly important for drugs that target specific intestinal regions or require delayed-release characteristics. This level of control over drug release is achieved by adjusting the ratio of acidic and neutral monomers in the polymer matrix, further enhancing the precision of drug delivery.

7.2 Lipid-Based Coatings for Sustained Release

Lipid-based coatings offer a different approach to drug delivery, relying on hydrophobicity rather than solubility to control drug release. These coatings, often composed of materials such as glyceryl behenate and hydrogenated castor oil, form an impermeable barrier that regulates water penetration and drug diffusion, creating a sustained release profile. Lipid coatings are particularly beneficial for drugs requiring prolonged therapeutic effects, such as those used in the management of chronic conditions like hypertension or diabetes. By controlling the thickness and composition of the lipid layer, pharmaceutical formulators can create systems that release the drug over an extended period, reducing dosing frequency and improving patient compliance. (Seo et al, 2020).

Sustained-release formulations are critical for managing recurring diseases, as they maintain steady plasma drug levels, thereby preventing the fluctuations associated with conventional immediate-release formulations. These coatings have been used successfully in medications such as antihypertensives, which benefit from reduced dosing frequency and improved therapeutic efficacy. Lipid coatings also offer the advantage of minimizing potential gastric irritation that some drugs may cause, ensuring a safer and more effective drug delivery process.

7.3 Nanoparticle Coatings and Precision Delivery

Nanoparticle-based coatings represent a cutting-edge advancement in drug delivery technologies, offering unique advantages over traditional coating materials. Nanoparticles' small size, large surface area-to-volume ratio, and ability to be functionalized for specific purposes make them ideal for targeted drug delivery. Nanoparticles can be engineered to exhibit hydrophobic, hydrophilic, or amphiphilic characteristics, allowing for the precise control of drug release and targeting. For example, silica nanoparticles can improve the solubility of poorly water-soluble drugs, while chitosan nanoparticles can enhance drug retention and absorption in the gastrointestinal tract by leveraging their mucoadhesive properties (Reddy et al,2013).

The use of nanoparticles for targeted drug delivery is especially valuable in oncology, where drugs with narrow therapeutic indices

need to be delivered precisely to tumor cells. Nanoparticle coatings can encapsulate chemotherapeutic agents, reducing systemic toxicity and ensuring that the drug is concentrated at the tumor site. This precision significantly improves therapeutic efficacy and minimizes the side effects that typically accompany cancer treatments. Furthermore, nanoparticle coatings offer the flexibility to integrate multiple functionalities, such as enhanced solubility, sustained release, and targeted delivery, making them suitable for complex therapeutic regimens.

However, despite their promising advantages, the application of nanoparticles in tablet coatings presents challenges. The complexity of nanoparticle systems, along with their high production costs, limits their widespread use. Moreover, concerns regarding their potential toxicity and long-term accumulation in the body must be addressed before they can be adopted on a large scale. Research into improving nanoparticle stability, manufacturing processes, and safety profiles is critical for their successful integration into commercial formulations.

7.4 Hybrid Coatings and Future Trends

One of the most promising avenues for future research is the development of hybrid coatings that combine the strengths of multiple materials. For instance, combining enteric polymers with nanoparticles could provide both pH-sensitive release and targeted drug delivery. This approach has the potential to address the limitations of individual coatings and offer more comprehensive solutions for complex drug delivery challenges. Hybrid systems could also be tailored to meet the specific needs of drugs with unique pharmacokinetics or therapeutic goals.

Furthermore, advancements in technologies such as 3D printing and nanotechnology are opening new possibilities for the creation of next-generation drug delivery systems. 3D printing allows for precise control over the structure and composition of tablet coatings, enabling the production of customized formulations with optimal release profiles. Also, 3D Printing Technology is also being utilized for the packaging systems of drug products. (Vahora et al. 147) . Similarly, nanotechnology promises to enhance the functionality of tablet coatings, improving drug stability, solubility, and targeting capabilities.

In conclusion, tablet coatings play a pivotal role in optimizing drug delivery systems by influencing factors such as drug stability, release kinetics, and bioavailability. The careful selection of coating materials, whether enteric polymers, lipid-based coatings, or nanoparticles, is crucial for achieving specific therapeutic goals and addressing the unique challenges posed by different drugs. Future research should focus on developing hybrid coatings and leveraging emerging technologies to enhance the precision, effectiveness, and scalability of drug delivery systems. As advancements in material science and nanotechnology continue to evolve, the potential for creating more efficient, patient-centered drug delivery solutions will expand, leading to improved therapeutic outcomes and enhanced patient compliance.

8. Conclusion

This study highlights the essential role of tablet coatings in optimizing drug delivery systems. Enteric polymers, lipid-based coatings, and nanoparticles each offer distinct benefits, including pH-sensitive release, sustained drug delivery, and enhanced bioavailability. However, selecting the appropriate coating material requires a thorough understanding of the drug's specific properties, therapeutic objectives, and pharmacokinetic profile.

Future research should focus on developing hybrid coatings that leverage the strengths of multiple materials, such as combining enteric polymers with nanoparticles to enable both targeted delivery and improved permeability. Additionally, emerging technologies like 3D printing and advancements in nanotechnology offer promising avenues for creating next-generation drug delivery systems. Ultimately, this study provides valuable insights for pharmaceutical scientists, guiding the development of more efficient, patient-centered drug delivery solutions that address diverse therapeutic needs.

Author contributions

All authors made equal contributions to the study design, statistical analysis, and drafting of the manuscript. The corresponding author, along with the co-authors, reviewed and approved the final version of the article prior to submission to this journal.

Acknowledgment

The authors were grateful to their department.

Competing financial interests

The authors have no conflict of interest.

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